The fourth workshop on nonlinear processes in space plasmas: epilogue and telesis

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1 Introduction

On the last day of the workshop, a panel discussion was held to assess the work of the meeting, and consider the present status of this field. The panel consisted of C. Cattell, V. Hansteen, G. Morales, F. Skiff, H. Pecseli, P.-L. Sulem, and the author. This was a chance for the panel and the entire group of participants to look beyond the important details of various mathematical approximations, frequency responses of spacecraft wave instruments, etc. This session was also a chance to make a list of those results in which we have the most confidence, and to "apply our intellectual perception to such objects as are apt to call it forth, and attract it to its own proper good and advantage" (Plutarch, 110).

Two questions were put to the panel and the audience. In the first, participants were asked to identify those presentations which they had found most interesting. The second question was more provocative[1], and asked in what direction the field of space plasma physics should move in the next five to ten years.

2 The best (or at least most popular) of the presentations

A number of themes struck the panel as being particularly intriguing, significant, or novel relative to previous workshops in this series.

2.1 Laboratory experiments

For the past several decades, plasma astrophysics has been nearly exclusively a theoretical discipline. This is not the sign of a healthy branch of physical science, and has no doubt impeded the contributions that plasma astrophysics could have made to our understanding of the universe. The workshop displayed an impressive improvement in this situation, and laboratory results were presented which promise more direct application to space and astrophysical plasmas. There are a number of reasons for this happier state of affairs, the primary being the construction of large machines that are several to many ion inertial lengths in size. Since much of plasma astrophysics deals with magnetohydrodynamic phenomena (interstellar turbulence, particle acceleration, plasma effects on star formation), the advent of these machines has made experimental physics more relevant to astronomy and astrophysics.

Other advances in the relevance of experiments have resulted from improvements in the kind and quality of diagnostic measurements. Laser fluorescence experiments permit spatially-resolved measurements of ion distribution functions, a major advancement on techniques of the past, which relied on more ambiguous probe measurements.

Other topics discussed in the workshop have had relevant laboratory experiments for some time, and one can now sense the benefits of collaboration and "synphronesis" between the space physics and plasma physics communities. Experimental studies of electrostatic waves and instabilities of relevance to the aurorae are being carried out, with the inclusion of realistic aspects such as velocity shear.

2.2 Electron holes

A number of members of the panel and audience were impressed by the substantial corpus of work on electron holes, or BGK modes as they are named under an alias. The fascination of these objects is in part due to their adherence to basic statements of fundamental plasma physics. Their very existence corroborates our faith in the Vlasov-Maxwell equations, and incites a full-throated, Boris-Godunov-like chanting of the Nonlinear Waves and Chaos Anthem. Beyond this, however, if their discovery and description is to have the status of a major discovery, these holes must do something.

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[1] At least in a manner of speaking. It is difficult to be exceedingly provocative when dealing with subject matter of the sort that interests us.

That is, they should represent a major new and superior way of describing an important class of electrostatic waves, or they must be shown to be crucial in a major plasma physics process, such as ion acceleration or heating of the corona. The connection, if any, between electron holes and Alfvénic turbulence should also be examined. Such a connection may be suggested because Alfvénic turbulence seems to be capable of generating parallel electric fields, and these electric fields might spawn the electron holes. The significance (rather than merely the existence) of these objects could be one of the goals of a future meeting in this series, perhaps the one to be held in Bombay in 2003. At this forthcoming meeting we could also examine the extent to which the electron holes serve as a model of other "coherent phenomena" emergent from turbulent plasmas.

2.3 Cluster spacecraft and multi-point measurements

This workshop was the first of its series subsequent to the commissioning of the Cluster spacecraft. Although dual spacecraft measurements have been utilized in the past (ISEE 1 and 2 being a prominent example), Cluster will constitute a major dedicated instrument for this type of investigation. It should be capable of disentangling spatial from temporal fluctuations, and will provide information on the symmetry of plasma fluctuations. The presentations at the workshop described Cluster data in an inchoate state, but the panel felt that they already represented "a qualitatively different type of measurement". Many practical data analysis issues remain to be ironed out. However, these data give a clear idea of what can be expected in the future, as this instrument helps address issues such as the degree of coherence of electrostatic noise in auroral regions.

2.4 New ideas

Generally speaking, talks at a meeting such as this will closely resemble ones previously presented, thus representing a rephrasing of ideas already expressed. Human beings take comfort in litanies which state the known and secure. However, what is good for primitive societies is not good for science, so it is of interest to see the emergence of new ideas. Such ideas may explain hitherto poorly understood phenomena. There were at least two such developments at this meeting. The first was the suggestion, or rather recognition, that plasma waves will vary in degree and kind in a non-Maxwellian plasma. Discernible differences have been observed and measured in laboratory plasmas which differ only slightly from Maxwellians. They will presumably be far more pronounced in media, such as the solar wind and other astrophysical plasmas, where the departures from Maxwellian are substantial.

The second new development was a suggestion emergent from laboratory experiments on Alfvénic turbulence. These experiments show that Alfvén waves can generate field-aligned current filaments, which produce spatial inhomogeneity on a scale smaller than the initial wave. These inhomogeneities, in turn, generate new Alfvén waves on scales comparable to and smaller than the current channels. This suggests the possibility of a continued and progressive nesting of such structures, in which waves generate current channels, which, in turn, generate Alfvén waves, ad infinitum. This sounds very much like a cascade from large scales to small, although via physical processes quite different from those usually discussed, such as vortex stretching, wave-wave interaction, and differential $\boldsymbol{J} \times \boldsymbol{B}$ forces. Whether these experiments have pointed out a new, and potentially more useful view of an MHD turbulent cascade remains to be determined by future investigators, and may find itself on the program of a future nonlinear waves and chaos meeting.

3 The future of nonlinear plasma physics in space

3.1 Quid sit futurum cras, fuge quaerere. . .Horace[2]

The second question addressed to the panel and the audience concerned the status of the field 5–10 years in the future. This exercise can have the useful function of identifying areas in which we might focus attention, people, and money. It also has the salutary effect of making us critically assess the field as a whole. Once again, the discussion revealed a number of common themes.

3.2 Beyond magnetohydrodynamics

Single and two fluid magnetohydrodynamic models of plasmas have served the space and astrophysical plasma communities well. Theory based on these models has provided many basic theoretical results which are the foundation of the field, such as the Alfvén wave, the Parker solution for the structure of the solar wind, mathematical models for plasma turbulence, and the basic framework of magnetic reconnection. There have been a number of successes in these areas. Nonetheless, it is increasingly clear, and was illustrated by the discussions and presentations at this meeting, that the real phenomena in space plasmas also demand a description in terms of kinetic effects. Future theories must develop a hybrid of the MHD equations and the Vlasov equation, or even some new approach which contains both fluid behavior and wave-particle interactions.

An example which is both specific and of great importance is that of magnetohydrodynamic turbulence. A major and robust result from theories such as reduced magnetohydrodynamics is that ever smaller and more intense current and vorticity sheets will develop from a broad class of initial conditions (see, for example, Dmitruk, Milano, and Matthaeus 2001, for an entry point to the literature). It is clear that this development leads to dissipation of some sort, most probably on the ion-inertial scale, but calculations to date have only utilized ad-hoc models for the turbulent damping. A satisfactory description of plasma turbulence will re-

[2]Carmen V. I., Liber I. "Shun the attempt to know what will happen tomorrow"

quire a similarly satisfactory theoretical description of the dissipation, and that will require kinetic theory. Dissipation in most astrophysical plasmas will occur via collisionless mechanisms. These anticipated developments should provide a self-consistent closure of the equations of turbulence theory, and should give us better descriptions of phenomena in media such as the solar wind.

Another product of progress beyond MHD descriptions would be a better understanding of how Alfvén waves can generate parallel electric fields. Observations, some of which were discussed in this workshop, indicate that these parallel fields are common and probably important to plasma dynamics. Ideal MHD obviously has no way of describing these fields beyond negligible resistive effects. Theoretical work incorporating more terms in the generalized Ohm's Law has begun in the last few years. Further work in this direction can be anticipated and should be encouraged, and can provide intermediate steps to more accurate Vlasov theory descriptions of magnetic field-aligned electric fields.

3.3 Nonlinear waves with growth and dissipation

A major theme of this workshop, reflected even in its title, is the behavior of nonlinear waves in space plasmas. Many researchers have been drawn to studies of nonlinear wave equations, such as the Nonlinear Schrödinger equation and the Derivative Nonlinear Schrödinger equation. There has been a tendency to focus attention on solutions of the ideal equations, i.e. those without growth and damping. In the case of the aforementioned equations, there are then only two physical processes operative, nonlinearity and dispersion. In this case, these equations have a variety of appealing mathematical properties, such as derivability from Lagrangian densities, an infinity of conserved quantities, inverse scattering transforms, etc.

E. Mjølhus made the good point that the real waves in space plasmas are both driven and dissipated, and that these nonconservative processes should be taken into account when these equations are used as models of space and astrophysical phenomena. The driven and damped equations lack some of the mathematical beauty of the conservative, "completely integrable" equations, but they will be a better description of the waves which occur in nature. Investigations in this area could also serve as an entry point for another intriguing suggestion, i.e. that the plasmas we study in nature are media far from equilibrium (the solar wind at 1 a.u. certainly qualifies in many respects) and that we should be alert for lessons from another field, biology, that points to the importance of non-equilibrium statistical mechanics.

3.4 A common language

This workshop is unique, or at least highly unusual, in featuring participation from plasma theorists, space experimentalists, and astronomers, and it deals with phenomena from a number of natural plasma media. Future workshops in this series should continue the conceptual integration of theory, computer simulation, spacecraft observations, and experiment. In view of this, every effort should be made to present results, theoretical, observational, and experimental, in a form that is maximally intelligible to other scientists. This could be accomplished by presenting results on fluctuations in magnetic field and density in terms of normalized field variables. Length and time scales should be treated similarly.

3.5 Coupling between large and small scales

A universal characteristic of turbulence in space and astrophysical plasmas is the existence of fluctuations on a wide range of spatial scales. This characteristic is also possessed by turbulence in other media, such as the atmosphere. The full extent of the relationship between the fluctuations on different scales is not entirely clear, however. Almost by default, it is assumed that the sixty year old Kolmogorov picture, developed for hydrodynamic turbulence, is valid for turbulence in collisionless plasmas. In the Kolmogorov picture, the cascade is forward and local in wave number space, beginning at a lowest wave number corresponding to a well-defined stirring scale, and proceeding to dissipation at a small viscous or resistive scale. This picture has persisted despite growing evidence (such as that provided by the plasma of the interstellar medium) that there must be more to the story.

The general theme of the turbulent cascade, and interactions between fluctuations on different scales, is related to another topic discussed in the meeting and the panel. This is the modification in the nature of turbulence which occurs in nonuniform plasmas. The theoretical idea of turbulence existing in a background plasma which is spatially uniform and temporally invariant is mathematically convenient. However, plasmas in space generally have pronounced spatial and temporal modulation that cannot really be considered turbulent in nature. An obvious example would be solar wind inhomogeneity due to the sector structure. In inhomogeneous plasmas, instabilities can be substantially modified and diagnostic relations between field variables can be changed. Although recognition of this fact is not novel, and work has been done in the past, more research efforts is warranted in the future.

3.6 Beyond the heliosphere

As a result of several decades of research in space plasma physics, we have acquired a rather sophisticated understanding of many plasma phenomena in the solar system, such as magnetohydrodynamic turbulence, collisionless shock waves, and charged particle interaction with and acceleration by shocks and turbulence. In the same time period, it has become clear that closely analogous and perhaps identical phenomena occur in more remote astrophysical plasmas. Examples would include the interstellar turbulence responsible for radio wave scintillation, strong shock waves associated with supernova remnants, and the acceleration and transport of the galactic cosmic rays. This suggests that plasma physicists in general, and space plasma physicists in particular, should extend their interests to the astronomical universe. In concert with this development, more effort could and should be devoted to the development of remote sensing techniques. It will not be possible to insert magnetometers and plasma analysers in all media of interest. We should extend and improve already existing techniques which utilize optical and UV spectroscopy and radio propagation measurements. There should also be effort to develop new concepts in remote sensing.

4 A worry for the future: where are the new researchers and students?

"Once they blackened the plains with their numbers; the Earth shook when they moved..." [3]

The final point to be made in this summary is a sobering one. The panel and audience discussed whether the equation of continuity is being obeyed for scientists in our field. A vital field of scientific research requires an influx of young, vigorous scientists who will insure continuation and evolution of a discipline. A glance over the audience at this panel revealed an excess of gray heads, slack jaws, and individuals who had succumbed to senile slumber[4]. How then do we help undergraduate and graduate students at our universities to share our enthusiasm and vision for this field?

This is a problem which is difficult to address, and which is not peculiar to our area of physics. We should redouble our efforts to involve students, both undergraduates and graduate, in our research. A student who becomes involved, interested, and knowledgeable in a field is likely to continue and plan a career in that area of science. Beyond this, we can plan research programs that come to grips with big issues in science, and capture the imagination of young student scientists.

Acknowledgements. All participants in the meeting will long remember its stunning location, superb organization, and comfort and convenience. We all thank E. Mjølhus and K. Rypdal for their efforts in organizing the meeting.

References

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Plutarch, Life of Pericles, (circa) 110.

[3] An often used and lyrical description of the two huge herds of buffalo which roamed the American West prior to the arrival of European settlers. They were later hunted nearly to extinction.

[4] I will not discuss the alternative interpretation of the data, i.e. that the subject matter and discourse of this panel discussion would have induced a comatose state even in the young and virile.